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Machining Processes and Machines

Fundamentals, Analysis, and Calculations

Zainul Huda

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Preface

Machining/Material Removal Processes is taught as a full Manufacturing-2 course in undergraduate Mechanical Engineering programs in almost all reputed universities. This book, therefore, covers fundamentals and engineering analysis of both conventional and advanced material removal processes, along with gear cutting/manufacturing technology and computer numerically controlled (CNC) machining.

This textbook provides a holistic understanding of machining processes and machines, and enables critical thinking through mathematical modeling and problem-solving. The salient features of this text include 200 calculations/worked examples, 70 MCQs (with answers), 120 diagrams/photographs, and around 200 equations on machining operations, including gear cutting and CNC machining. The book is equally useful to both engineering-degree students and production/design engineers practicing in manufacturing industry; the latter may specially benefit from highly practical stuff on gear cutting/manufacturing (Chapter 10).

The book is divided into four parts. *Part I* (Chapters 1–4) first introduces readers to machining, machinability, types of machining processes, and theory of metal cutting, followed by a discussion on cutting tools and materials. In this *Part*, a detailed analysis of mechanics of chip formation and cutting forces are presented. *Part II* (Chapters 5–10) deals with conventional machining operations, including gear cutting/manufacturing. Here, special emphasis is given to turning, drilling, milling, and broaching, including their engineering analyses and problem solving.

Part III (Chapters 11 and 12) first introduces readers to grinding wheels and their specifications, followed by discussions on grinding operations and abrasive finishing machining operations. Here, the techniques to achieve a good surface finish by controlling grinding parameters are established. In this *Part*, grinding operations are first described and mathematically modeled, and grinding machines' working is illustrated; then abrasive finishing machining operations (honing, lapping, super-finishing, etc.) are explained, including their engineering analysis.

Lastly, *Part IV* (Chapters 13–16) presents advanced machining technologies. Here, computer numerically controlled (CNC) machines are introduced, along with the mathematical modeling of CNC machining. The chapter on CNC machining covers both computer aided design (CAD) and computer aided manufacturing (CAM), along with their mathematical modeling and problem solving. This *Part* also deals with non-traditional machining processes; these include ultra-sonic machining (USM), water jet machining (WJM), abrasive water jet machining (AWJM), abrasive jet machining (AJM), electric discharge machining (EDM), electric discharge wire cutting (EDWC), electron beam machining (EBM), laser beam machining (LBM), electro-chemical machining (ECM), and chemical machining (ChM). Almost all the non-traditional material removal processes are mathematically modeled.

This book contains 16 chapters. Each chapter first introduces readers to the technological importance of the topic and provides basic concepts with diagrammatic illustrations, and then its engineering analysis/mathematical modeling, along with calculations are presented. An attempt is made to use SI units in each mathematical

model throughout the text. There are altogether **200 worked examples/calculations, 120 diagrams/photographs, 70 MCQs (with answers)**, and around **200 mathematical models/equations.** In particular, the worked examples cover solutions to both simple and difficult-to-solve problems. In order to best benefit from this book, the student/reader is advised to first prepare a list of relevant formulae and then attempt to solve a problem (worked example) while hiding its solution; they must try to solve the problem on their own by analyzing the data. In case the reader is stuck during solving the problem, they may refer to its solution. *Question and Problems* are included at the end of each chapter. The end-of-chapter problems must also be solved by the student/reader following the verification of their respective answers; the latter are provided at the end of the book. Based on my long-term associations with academia and industry, I anticipate that this volume proves a useful literature for both engineering students and practicing engineers. In particular, engineers/machine shop managers may greatly benefit from the 200 worked examples/calculations.

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Author

Besides this book, **Professor Zainul Huda** (ORCID ID: 0000-0002-3433-4995) is the author of 6 books, including *Manufacturing: Mathematical Models, Problems, and Solutions* (CRC, Press, 2018) and *Metallurgy for Physicists and Engineers Fundamentals, Applications, and Calculations* (CRC Press, 2020). Dr. Zainul Huda is a Professor of Manufacturing Technology at the Mechanical Engineering Department, King Abdulaziz University (KAU), Jeddah, Saudi Arabia. His teaching interests include Material Removal Processes, Manufacturing Technology, Metallurgy, and Mechanical Behavior of Materials. He (as a *PI*) has recently completed a funded research project on autonomous robots. He is also a *PI* in another SAR 35,000 research project on boilers' super-heater tubes material. He has been working as a full Professor in reputed world ranking universities (including University of Malaya, King Abdulaiz University, King Saud University, etc.) since February 2007. Prof. Huda has 40 years' professional experience in materials, manufacturing, and mechanical engineering. He is a Professional Engineer (PE) registered under Pakistan Engineering Council. He has worked as Plant Manager, Development Engineer, Metallurgist, and Graduate Engineer in various manufacturing companies, including Pakistan Steel Mills Corporation Ltd. Prof. Huda earned a PhD in Materials Technology from Brunel University, London, UK, in 1991. He is also a postgraduate in Manufacturing Engineering. He obtained B. Eng (Metallurgical Engineering) from the University of Karachi, Pakistan, in 1976.

Prof. Huda is the author/co-author of a patent and 130 publications, which include 7 books, 36 international peer-reviewed journal articles (27 ISI-indexed journal articles), and many conference proceedings in the fields of materials, manufacturing, and mechanical engineering, published by reputed publishers from the USA, Canada, the UK, Germany, France, Switzerland, Pakistan, Saudi Arabia, Malaysia, South Korea, and Singapore. He has been cited over 800 times in Google Scholar. His author's h-index is 13 (i10: 18). He (as a *PI*) has attracted nine (9) research grants, worth total of USD 0.16 million. He has also successfully completed 20+ industrial consultancy/R&D projects in the areas of failure analysis and manufacturing in Malaysia and Pakistan. He is the developer of Toyota Corolla cars' axle-hub's heat treatment procedure, first-ever implemented in Pakistan (through Indus Motor Co/ Transmission Engineering Industries Ltd, Karachi). Prof. Huda has delivered guest lectures in the UK, South Africa, Saudi Arabia, Pakistan, and Malaysia. He is a Member of prestigious societies, including Institution of Mechanical Engineers (*IMechE*), London, UK; Canadian Institute of Canadian Institute of Mining, Metallurgy and Petroleum (CIM), Canada; and Life-time Member of Pakistan Engineering Council. Prof. Zainul Huda is the world's Top 20 (#14) scholar in the field of *Materials and Manufacturing* (see www.scholar.google.com).

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Part I

Fundamentals of Machining and Cutting Tools

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1 Introduction

1.1 WHAT IS MACHINING?

Machining is a subtractive manufacturing process that involves material removal, usually in the form of chips, from a workpiece. In machining, material is removed from a workpiece by using either a cutting tool or an energy source. In traditional machining, material removal is accompanied by the formation of chips, which is accomplished by use of a cutting tool with cutting edge(s). On the other hand, non-traditional machining (NTM) processes are chip-less material removal processes that involve the use of energy for material cutting. The traditional machining operations include turning, drilling, milling, shaping/planing, broaching, grinding, and the like (see Section 1.3).

Machining may be considered as a system consisting of the workpiece, the cutting tool, and the equipment (machine tool). In machining, there exists a relative motion between the tool and the work; the primary motion is called *cutting speed*, whereas the secondary motion is called *feed*. In general, there are three fundamental cutting conditions: (a) cutting speed, (b) feed, and (c) depth of cut. *Cutting speed* is the greatest of the relative velocities of cutting tool or workpiece. For example, in turning machining operation, the surface speed of the workpiece is the *cutting speed* (v), usually expressed in m/min (see Figure 1.1). *Feed* (f) is the distance moved by the tool (or by the work) per revolution, usually expressed as mm/rev. *Depth of cut* (d) is the distance the cutting tool penetrates into the work.

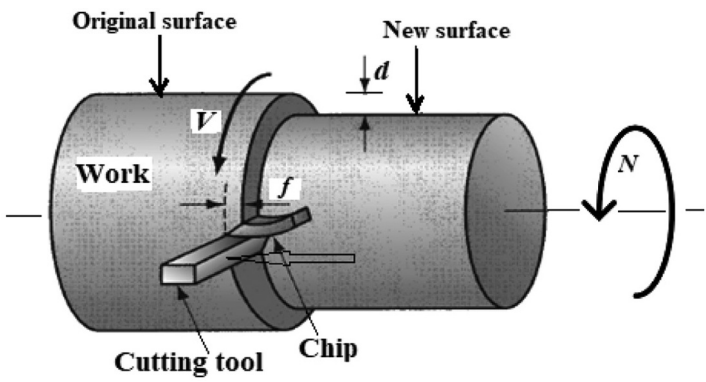

FIGURE 1.1 Turning operation (d = depth of cut; f = feed, V = surface speed, N = rotational speed)

1.2 INDUSTRIAL APPLICATIONS OF MACHINING

A wide range of engineering industries heavily rely on machining operations for manufacturing their products. In fact, machining is one of the eight basic manufacturing processes (metal casting, polymer/ceramic molding, metal forming, powder metallurgy, machining, welding/joining, heat treatment, and surface engineering). In general, cast, formed, and molded products require machining/material removal to achieve accurate dimensions and desired finish. The material removal machines are used for cutting metallic and non-metallic solids (e.g., metal, ceramics, wood, plastics, etc.). These machines find wide applications in diversified engineering industries. For example, the aerospace industry relies on machines with a high level of precision and accuracy to manufacture aircraft parts that fit the exact specifications of aeronautical design. Biomedical manufacturing companies produce life-saving devices that are used in hospitals and clinics across the world. The manufacturing of these life-saving devices and many other engineering components involves a great deal of machining operations. For example, gears and many machine elements can be manufactured by milling machining operations (see Chapters 7 and 10).

There are a number of advantages of machining processes which include (a) variety of work materials can be machined; (b) variety of part shapes and special geometric features are possible, such as screw threads and accurate round holes; (c) very straight edges and surfaces can be obtained; (d) good dimensional accuracy; (e) good surface finish; and (f) special geometric details can be created. In particular, the use of computer numerically controlled machines and other advanced machining technologies enables us to machine parts with high precision and productivity. However, there are also some limitations of machining/material removal processes; these disadvantages mainly include (a) wastefulness of materials in the form of chips, (b) time consumed in machining, and (c) the cost of machining.

1.3 MACHINING PROCESSES: CLASSIFICATION AND TYPES

1.3.1 Classification of Machining Processes

There exist a large number of material removal processes to fulfill the basic requirements of machining. All machining processes can be broadly classified into four categories: (a) conventional machining processes, (b) grinding and other abrasive machining processes, (c) NTM processes, and (d) micro-precision and ultra-precision machining (UPM) processes (see Figure 1.2). The four groups of machining processes are briefly discussed in the following sub-sections.

1.3.2 Conventional Machining Processes

Conventional machining processes involve the use of machine tools, such as lathes, milling machines, drill presses, shaper, or others, with a sharp cutting tool that removes material to achieve the desired geometry. The cutting tool may be either a single-point tool or a multiple-point cutting tool. Notable examples of conventional machining processes include *turning*, *drilling*, *milling*, *shaping*, *broaching*, and

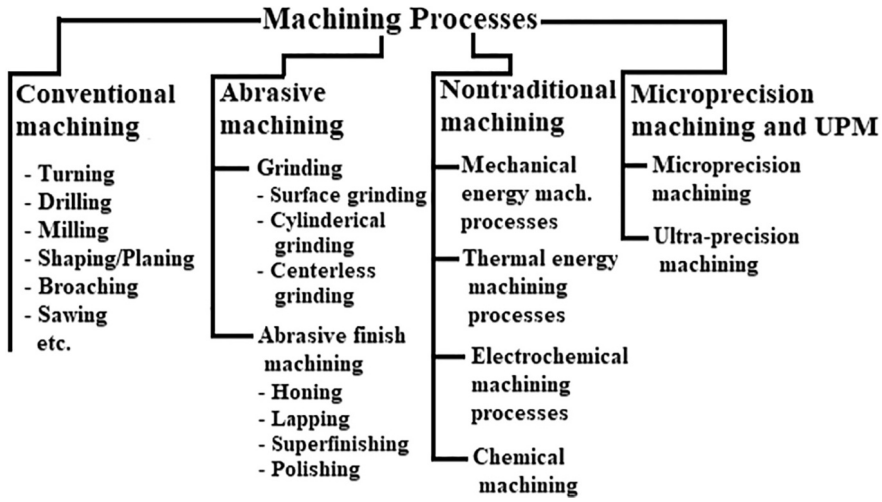

FIGURE 1.2 Classification of machining processes

the like. *Turning* involves the removal of material from a rotating cylindrical workpiece by the use of a single-point cutting tool; the latter has a feed motion (see Figure 1.1). *Milling* involves the use of a rotating cutter with multiple-point cutting edges; here, the cutting tool has the speed motion, and the work has feed motion. A detailed account of conventional machining processes is given in Part II (Chapters 5–10).

1.3.3 Abrasive Machining Processes

An abrasive machining process involves the use of a grinding wheel, an abrasive stick, or an abrasive suspension to remove material from a workpiece. *Grinding* is a material removal operation by the action of hard and abrasive particles that are bonded usually in the form of a wheel (grinding wheel). As indicated in Figure 1.2, a grinding operation may be surface grinding, cylindrical grinding, or center-less grinding. The abrasive finishing machining operations include honing, lapping, superfinishing, and the like. Grinding and other abrasive machining processes are explained in detail in Part III (Chapters 11 and 12).

1.3.4 Non-Traditional Machining

Non-traditional machining (NTM) processes are chip-less material removal processes that involve use of energy for material cutting. The NTM processes may be classified into four groups: (a) mechanical energy-based machining processes, (b) thermal energy-based machining processes, (c) electro-chemical machining (ECM) processes, and (d) chemical machining process (see Figure 1.2). The mechanical energy machining involves the removal of material by mechanical erosion or abrasion; these processes include ultra-sonic machining (USM), water jet machining (WJM),

abrasive WJM, and abrasive jet machining (AJM). Thermal energy machining relies on heat energy that causes removal of material by melting or vaporization; these processes include electric discharge machining, electric discharge wire cutting, electron beam machining, and laser beam machining. ECM processes are based on anodic metal dissolution in the presence of an electrolyte. The NTM processes are discussed in detail in Chapters 14–16.

1.3.5 Micro-Precision Machining and UPM

Micro-precision machining and UPM are playing a vital role in advanced manufacturing. *Micro-precision machining* is defined as "a manufacturing technology that involves the use of mechanical micro-tools with geometrically defined cutting edges in the subtractive fabrication of devices or features with at least some of their dimensions in the micrometer range (1–999 μm)" (Mativenga, 2014). Micro-precision machining processes enable us to produce micro-components, micro-features, and micro-structures.

Ultra-precision machining (*UPM*) is defined as "a machining process whose accuracy has been driven to its ultimate technological limits, irrespective of the nature of the process and the size of the workpiece (macro-, micro-, or nanoscopic)" (Brinksmeier, 2014). UPM processes allow us to achieve surface roughness down to nanometer scale; they are applied to manufacture optical components and similar components (Kang and Ahn, 2007; Schneider et al., 2019). For example, *diamond turning*, also called *single-point diamond turning*, is a *UPM* technology that involves the use of geometrically defined single-point diamond cutting tools for generating complex functional surfaces by turning operation (see Figure 1.3).

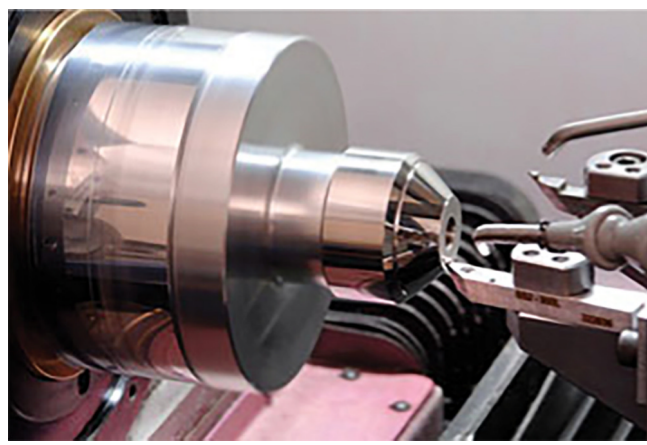

FIGURE 1.3 Machining of a complex geometry (conical shaped) work by diamond turning

1.4 ROUGHING AND FINISHING IN MACHINING

In conventional machining processes, it is often desirable to remove high stock from the bulk material (solid) as well as to achieve reasonably good surface quality. However, the achievement of both the objectives in a single pass is not possible. Thus, machining is usually carried out in two steps with varying cutting conditions (cutting speed, feed, and depth of cut). The two steps in machining are (a) roughing pass and (b) finishing pass. In the *roughing pass*, a bulk amount of material is quickly removed from the workpiece as per required feature. In this step, higher feed rate and depth of cut are employed so as to achieve a high material removal rate from the work. The roughing pass creates a shape close to desired geometry but leaves some machining allowance (material unremoved) for finish cutting. The roughing pass cannot provide good surface finish and close tolerance. This is why a *finishing pass* is carried out to improve surface finish, dimensional accuracy, and tolerance level; here, the feed rate and depth of cut are low. Thus, the material removal rate (MRR) is reduced in the finishing pass, but the surface quality is improved. Table 1.1 presents the main differences between roughing and finishing in conventional machining processes.

1.5 MACHINABILITY AND MACHINABLE MATERIALS

1.5.1 Machinability

Machinability refers to the ease of machining a material to obtain desired results at low cost. There are a number of quantitative measures of machinability; these measures include (a) tool life, (b) surface finish, and (c) other measures, such as cutting force, power, temperature, and chip formation. The tool life refers to the service time in minutes or seconds to a total failure of the cutting tool at certain cutting speed. The surface finish refers to the acceptable surface finish produced at standardized cutting speeds and feeds. A good machinability may mean one or more of the following: (a) minimum cutting forces, power, and temperature; (b) longer tool life (minimum tool wear); and (c) a good surface finish.

TABLE 1.1
Difference between Roughing and Finishing

Roughing in Machining	Finishing in Machining
It is performed prior to finishing pass	It is performed only after roughing pass
Its objective is to remove bulk excess material from workpiece in every pass	Its objective is to improve surface finish, dimensional accuracy, and tolerance
It involves higher feed rate and depth of cut	It involves higher cutting speed
It results in higher MRR	The MRR is low
The surface finish is poor	The surface finish is good
It cannot provide high dimensional accuracy and close tolerance	It can provide high dimensional accuracy and close tolerance
It permits the use of an old cutter	It requires the use of a sharp cutting tool

1.5.2 Machinable Materials

In order to perform machining with good machinability, the workpiece material should have the following properties/characteristics: (a) medium ductility; (b) reasonably low strain hardening exponent, shear strength, and fracture toughness; (c) presence of non-metallic inclusions that soften at high temperatures; (d) high thermal conductivity; and (e) a low metallurgical bond (adhesion) between cutting-tool and wokpiece.

Ductility directly affects the type of chip produced, which, in turn, affects surface finish. A brittle material (with a low ductility) may cause tool damage. On the other hand, very ductile materials tend to produce continuous chips that are difficult to control. Thus, medium ductility is desirable for good machinability. A work material with high thermal conductivity is helpful for dissipating heat to chips, resulting in cooler work during machining. It is important to avoid the embedding of very hard compounds (such as carbides, some oxides, and silicon) in the work material since these hard compounds accelerate tool wear.

Because steels are among the most commonly used engineering materials that are machined, the machinability of steel is generally improved by adding elements (e.g., lead, sulfur, etc.) or by heat treatment to change their properties. Besides free-machining steels, other good machinable materials include aluminum and its softer alloys, nodular cast irons, plastics, and nano-ceramics (Kalpakjian and Schmid, 2008).

1.6 INDUSTRIAL IMPORTANCE OF CALCULATIONS IN MACHINING

The calculations for various machining variables are of great technological importance in industrial practice. For example, the computation for spindle rotational speed in turning/drilling/milling enables a machinist to select the right spindle rpm in the machine tool. The computations for MRR in both traditional and NTM are also important for determining the efficiency and productivity. The calculation for the cutting time enables the machinist to complete the machining job well in time (Huda, 2018). The cutting time for a machining job also enables a machine shop manager to compute the labor cost in machining the job. The calculations for taper angle and tailstock offset in taper turning are important in the manufacture/machining of tapered shafts and other similar machine elements. The computation for MRR in NTM processes (e.g., AJM and ECM) is also important since the MRR enables a manufacturing manager to assess the efficiency and productivity of an NTM process.

The selection of an electric motor of correct horse-power (HP) to be attached to a machine tool is very important. In order to calculate the power required in machining, a machine-shop manager must calculate the cutting force by using a dynamometer as well as appropriate mathematical models. The cutting force calculations also enable a machinist to determine the degree of clamping required to hold a workpiece during machining. In gear manufacturing, the indexing calculations for both

plain and differential indexing are of great industrial significance. For example, calculations for the number of revolutions of index crank and for differential change gear ratio enable a machinist/engineer to select the correct differential change gears in an indexing head attached to a milling machine. All the abovementioned aspects of mathematical modeling and calculations in machining are covered in this textbook.

QUESTIONS

1.1 Encircle the most appropriate answers for the following statements.
   a. Which type of machining process is the drilling operation?
      (i) abrasive machining, (ii) conventional machining, (iii) NTM, (iv) Micro-precision machining
   b. Which type of machining process is the grinding operation?
      (i) abrasive machining, (ii) conventional machining, (iii) NTM, (iv) Micro-precision machining
   c. Which type of machining process is the electron beam machining?
      (i) abrasive machining, (ii) conventional machining, (iii) NTM, (iv) Micro-precision machining
   d. Which type of machining process is the diamond turning operation?
      (i) abrasive machining, (ii) conventional machining, (iii) NTM, (iv) Micro-precision machining
   e. Which type of machining process is the honing operation?
      (i) abrasive machining, (ii) conventional machining, (iii) NTM, (iv) Micro-precision machining
   f. Which type of NTM process is abrasive jet machining (AJM)?
      (i) mechanical energy machining, (ii) thermal energy machining, (iii) electro-chemical machining, (iv) chemical machining.
   g. Which type of NTM process is electro-chemical grinding?
      (i) mechanical energy machining, (ii) thermal energy machining, (iii) electro-chemical machining, (iv) chemical machining.
   h. Which type of NTM process is electric discharge machining (EDM)?
      (i) mechanical energy machining, (ii) thermal energy machining, (iii) electro-chemical machining, (iv) chemical machining

1.2 Define the term machining. List the three fundamental cutting conditions and define them.

1.3 Illustrate the various types of machining processes with the aid of a classification chart.

1.4 Differentiate between roughing and finishing in machining.

1.5 a. What is meant by machinability?
   b. What properties are required for a material to be machinable.
   c. Give at least three examples of machinable materials.

1.6 Highlight the industrial importance of machining and its mathematical modeling with examples.

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